

Final Report

Grant Title: Space-Time Code Designs for Broadband Wireless Communications

Grant Number: AFOSR # F49620-02-1-0157

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Reporting Period: 1 March 2002 – 31 March 2005

Proposed Award Period: 1 March 2002 – 31 March 2005

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A. Objective: The goal of this research is to design new space-time codes, such as complex orthogonal space-time block codes with rate above $1/2$ from complex orthogonal designs for QAM, PSK, and CPM signals, lattice based space-time codes, and unitary differential space-time codes for large number of transmit antennas. We want to study space-time code properties including fast decoding algorithms and performance and adaptivity to fading channels.

B. Main Research Accomplishments:

We have obtained numerous results on space-time code designs and fast decoding algorithms for multiple antenna systems. These results include new rate upper bounds of orthogonal space-time codes, systematic and closed-form designs of high rates orthogonal space-time block codes, orthogonal space-time coded continuous phase modulation (CPM), optimal full diversity and/or minimum maximum-likelihood decoding complexity quasi-orthogonal space-time codes, optimal cyclotomic space-time block codes, optimal unitary space-time block codes, new space-time trellis codes, systematic and new designs for recursive space-time trellis codes from differential encoding, full diversity distributed space-time trellis codes for asynchronous cooperative communication systems etc. More details on the main results we obtained can be summarized in the following categories.

B.1. *Orthogonal Space-Time Block Codes from Orthogonal Designs*

(i). *Upper bounds of orthogonal space-time block codes from orthogonal designs with infinite and finite signal constellations..* We derived some upper bounds of the rates of (generalized) complex orthogonal space-time (COST) block codes (with linear processing). We showed that the rates of COST block codes for more than 2 transmit antennas are upper bounded by $3/4$. We showed that the rates of generalized COST block codes for more than 2 transmit antennas are upper bounded by $4/5$, where the norms of column vectors may not be necessarily the same. We also presented another upper bound under a certain condition.

For a (generalized) complex orthogonal design, its variables are not restricted to any alphabet sets but are on the whole complex plane. We also studied a (generalized) complex orthogonal design with variables over some alphabet sets on the complex plane. We obtained a condition on the alphabet sets such that a (generalized) complex orthogonal design with variables over these alphabet sets is also a conventional (generalized) complex orthogonal design and therefore the above upper bounds on its

rate also hold. We showed that commonly used QAM constellations of sizes above 4 satisfy this condition.

What we should emphasize here is that the above results we obtained are not restricted to square codes and the time delays are arbitrary for a fixed number of transmit antennas.

(ii). *A closed-form design of complex orthogonal designs of rates $(k+1)/(2k)$ for $2k-1$ or $2k$ transmit antennas:* We obtained systematic and closed form constructions of complex orthogonal space-time block codes from complex orthogonal designs of rates $(k+1)/2k$ for $2k-1$ or $2k$ transmit antennas for any positive integer k , where the rates have been conjectured optimal.

(iii). *Orthogonal space-time block codes with APSK signals for differential modulation.* We obtained a differential en/decoding scheme for Alamouti's orthogonal space-time code using amplitude/phase-shift keying (STC-APSK) signals and two transmit antennas. It is compared with the differential en/decoding scheme using 16APSK and single transmit antenna. It is also compared with the differential en/decoding scheme for Alamouti's orthogonal space-time code using 16PSK (STC-16PSK) signals and two transmit antennas. We find that the performance of the differentially en/decoded STC-APSK with 4.5 bits/sec/Hz is significantly better than that of the differentially en/decoded 16APSK with 4 bits/sec/Hz, and is almost the same as that of the STC-16PSK with 4 bits/sec/Hz over Rayleigh flat fading channels.

(iv). *Unitary space-time codes from Alamouti's scheme with APSK signals:* Unitary space-time codes have been used in differential space-time modulation (DSTM), when neither the transmitter nor the receiver of a multiple antenna system knows the channel state information in Rayleigh fading channels. Among the codes in literature, unitary orthogonal space-time codes, constructed from Alamouti's scheme, have the advantage of fast maximum-likelihood (ML) decoding but they require signal constellations to be phase shift keying (PSK). In this work, unitary space-time codes are constructed from Alamouti's scheme with amplitude/phase shift keying (APSK) signal constellations. We show that the unitary space-time codes from Alamouti's scheme with APSK signals have better diversity products than those with PSK signals while the complexity of their ML decoding algorithm is comparable. Our newly proposed 4 bits/s/Hz code has about 2 dB gain over the same rate code with PSK signals at bit-error-rate (BER) of 0.001 with one receive antenna. We also propose a noncoherent scheme of rate 5 bits/s/Hz, which has the same BER performance with the 4 bits/s/Hz unitary orthogonal space-

time code in DSTM while they have comparable decoding complexity.

(v). *Quasi-orthogonal space-time block codes with full diversity and minimum decoding complexity and optimal symbol rotations..* Space-time block codes from orthogonal designs proposed by Alamouti, and Tarokh-Jafarkhani-Calderbank have attracted much attention lately due to their fast maximum-likelihood (ML) decoding and full diversity. However, the maximum symbol transmission rate of a space-time block code from complex orthogonal designs for complex constellations is only $3/4$ for three and four transmit antennas, and it is difficult to construct complex orthogonal designs with rate higher than $1/2$ for more than four transmit antennas. Recently, Jafarkhani, and Tirkkonen-Boariu-Hottinen, and Papadias-Foschini proposed space-time block codes from quasi-orthogonal designs, where the orthogonality is relaxed to provide higher symbol transmission rates. With the quasi-orthogonal structure, these codes still have a fast ML decoding, but do not have the full diversity. We achieved the full diversity by properly choosing the signal constellations. In particular, we proposed that half symbols in a quasi-orthogonal design are from a signal constellation set A and another half of them are from the rotated constellation $\exp(j\phi)A$. The resulting space-time block codes may have both full diversity and fast ML decoding. Furthermore, we obtained the optimal selections of the rotation angles ϕ for some commonly used signal constellations. In particular, we showed that the optimal rotation angle is $\pi/4$ if the signal constellation is from a square lattice and the optimal rotation angle is $\pi/6$ if the signal constellation is from an equilateral triangle lattice.

We systematically studied general linear transformations of information symbols for QOSTBC to have both full diversity and real symbol pair-wise ML decoding. We obtained the optimal transformation matrices (among all possible linear transformations not necessarily symbol rotations) of information symbols for QOSTBC with real symbol pair-wise ML decoding such that the optimal diversity product is achieved for both *general* square QAM and *general rectangular* QAM signal constellations. Furthermore, our newly proposed optimal linear transformations for QOSTBC also work for general QAM constellations in the sense that QOSTBC have full diversity with good diversity product property and real symbol pair-wise ML decoding. Interestingly, the optimal diversity products for square QAM constellations from the optimal linear transformations of information symbols we found coincide with the ones presented by Yuen-Guan-Tjhung by using their optimal rotations. However, the optimal diversity products for (non-square) rectangular QAM constellations from the optimal linear transformations of information symbols we found are better than the ones pre-

sented by Yuen-Guan-Tjhung by using their optimal rotations. In this paper, we also present the optimal transformations for the co-ordinate interleaved orthogonal designs (CIOD) proposed by Khan-Rajan for rectangular QAM constellations.

(vi). *Orthogonal space-time coded continuous phase modulation (CPM)*. The Alamouti orthogonal space-time block code is for QAM modulations and two transmit antennas. It is known that CPM systems with single transmit antenna have been widely used in wireless systems due to its spectral efficiency and resistance to wireless channel fading. In this research we have recently generalized it for the continuous phase modulation (CPM) by maintaining the orthogonality (for the fast ML decoding/demodulation) and the phase continuity of two signals from two transmit antennas. The orthogonality provides a fast Viterbi decoding/demodulation algorithm.

We also obtained an orthogonal space-time coded partial response CPM scheme with fast decoding algorithm.

B.2. Lattice Based Space-Time Block Codes.

(i). *Systematic and optimal cyclotomic space-time code designs based on high dimensional lattices and algebraic number theory*. A new systematic diagonal space-time block code (cyclotomic space-time code) design is proposed by using high dimensional cyclotomic lattices and algebraic number theory. This design can be applied to any number of transmit antennas and for a fixed number of transmit antennas, there are infinitely many cyclotomic space-time codes. It is shown that all the cyclotomic space-time codes from the design have full diversity. Furthermore, optimal cyclotomic space-time codes from the design for different numbers of transmit antennas are obtained, where the optimality is in the sense that, for a fixed mean transmission signal power, its diversity product is maximized, or for a fixed diversity product, its mean transmission signal power is minimized. Although there are some cyclotomic space-time codes existed in the literature, most of them are not optimal.

(ii). *Optimal multi-layer and single layer/diagonal cyclotomic space-time codes based on high dimensional lattices and Algebraic Number Theory*. We obtained a more general multi-layer cyclotomic space-time codes than the ones existed in the literature. We obtained a general optimality theorem for these infinitely many cyclotomic diagonal (or single-layer) space-time codes over general cyclotomic number rings for a general number of transmit antennas. We then obtained optimal multi-layer (full-rate) cyclotomic space-time code designs for two and three transmit antennas. We also obtained an optimal two-layer cyclotomic space-time code design for 3 and 4 transmit antennas.

We find that our design examples for two transmit antennas from our newly proposed optimal multi-layer cyclotomic space-time codes are about 3 dB better than the existing ones in terms of the symbol error rates versus signal-to-noise ratios for a fixed throughput.

(iii). *Diversity product upper bounds and some new designs for lattice based diagonal space-time block codes.*

We first obtained two tight upper bounds for the normalized diversity products (or product distances) of 2×2 diagonal space-time block codes from quadratic extensions on $\mathbb{Q}(i)$ and $\mathbb{Q}(j)$. Two such codes are shown to reach the tight upper bounds and therefore have the maximal normalized diversity products. We obtained two new diagonal space-time block codes from higher order algebraic extensions on $\mathbb{Q}(i)$ and $\mathbb{Q}(j)$ for 3 and 4 transmit antennas. We also obtained a non-tight upper bound for normalized diversity products of 2×2 diagonal space-time block codes with QAM information symbols, i.e., in $\mathbb{Z}[i]$, from general 2×2 complex-valued matrices. We then obtained an $n \times n$ diagonal space-time code design method directly from $2n$ real integers based on extended complex lattices (of generating matrix size $n \times 2n$) that are shown to have better normalized diversity products than the optimal diagonal cyclotomic codes do. We used the optimal 2×2 diagonal space-time codes from the optimal quadratic extensions to construct two 2×2 full rate space-time block codes and find that both of them have better normalized diversity products than the Golden code does.

(iv). *Diversity product determination of Lu-Kumar codes:* We have precisely determined the diversity product (coding advantage or product distance) for Lu-Kumar space-time block codes.

B.3. Full Diversity Distributed Space-Time Codes for Asynchronous Cooperative Communications

In current cooperative communication schemes, to achieve cooperative diversity, synchronization between terminals is usually assumed, which may not be practical since each terminal has its own local oscillator. In this research, we have constructed a family of space-time trellis codes for BPSK modulation scheme that is characterized to possess the full cooperative diversity order without the need of the synchronization assumption. The family is based on the stack construction proposed by Hammons and El Gamal. We have then generalized this family of space-time trellis codes from BPSK to higher order QAM and PSK modulation schemes based on the unified construction proposed by Lu and Kumar. We have shown that the construction of such a family is

equivalent to the construction of matrices that have full rank no matter the shifts of their row vectors, where a row corresponds to a terminal (or transmit antenna) and the length of a row vector is the memory size of the corresponding trellis code on the corresponding terminal. We call such matrices as shift full rank (SFR) matrices. A family of SFR matrices has been also constructed and the memory sizes of the corresponding space-time trellis codes (the number of columns of SFR matrices) grow exponentially in terms of the number of terminals (the number of rows).

B.4. Space-Time Trellis Codes

(i). *A new recursive space-time trellis codes based on differential modulation:* Differential space-time modulation (DSTM) has been recently proposed by Hughes, and Hochwald and Sweldens when the channel information is not known at the receiver, where the demodulation is in fact the same as the coherent demodulation of space-time block coding by replacing the channel matrix with the previously received signal matrix. On the other hand, the DSTM also needs a recursive memory of a matrix block at the encoder and therefore provides a trellis structure when the channel information is known at the receiver. This recursive structure of the DSTM has been adopted lately by Schlegel and Grant in joint with a conventional binary code and joint iterative decoding/demodulation with a superior performance. The number of states of the trellis from the recursive structure depends on both the memory size, which is fixed in this case, and the unitary space-time code (USTC). When a USTC for the DSTM forms a group, the number of states is the same as the size of the USTC, otherwise the number of the states is the size of the semi-group generated by the USTC from all the multiplications of the matrices in the USTC. It is well-known in the conventional convolutional coding (CC) or the trellis coded modulation (TCM), the free (Hamming or Euclidean) distance (or the performance) increases when the number of states increases by adding more memory with a properly designed CC or TCM. We systematically studied and designed the USTC/DSTM for the recursive space-time trellis modulation and show that the diversity product increases when the number of states increases, which is not because of the memory size but because of the different USTC designs that generate different sizes of semi-groups. We proposed a new USTC design criterion to ensure that the trellis structure improves the diversity product over the USTC as a block code. Based on the new criterion, we propose a new class of USTC design for an arbitrary number of transmit antennas that has an analytical diversity product formula for two transmit antennas. We then followed Schlegel and Grant's approach for joint encoding and iterative decoding of a binary coded DSTM (turbo space-time coding)

and numerically showed that our new USTC designs for the recursive space-time trellis modulation outperforms the group USTC used by Schlegel and Grant.

We have also obtained a general space-time differential encoding for the above concatenated system by introducing a new multiplication for information matrices such that the error event length of the recursive trellis from the differential encoding is at least 3 and therefore better diversity products can be achieved for the inner space-time trellis codes.

(ii). *Super-orthogonal space-time trellis codes based on non-PSK MTCM*: Super-orthogonal space-time trellis codes recently proposed in the literature are space-time trellis codes of full diversity and high rates systematically constructed by concatenating orthogonal space-time codes and multiple trellis coded modulation (MTCM). However, the existing MTCM only has designs for PSK signals. We have extended MTCM from PSK signals to non-PSK signals in some special cases. With obtained constellations of MTCM, several super-orthogonal space-time trellis codes for two transmit antennas are presented. The 2, 4-state codes have a simple mathematical expression for the coding gain distance (CGD), or diversity products. At rates 2.5, 3, 3.5, 4 bits/s/Hz, the newly proposed codes outperform the existing ones.

(iii). *Super orthogonal differential space-time trellis coding and decoding*: We proposed a differential space-time trellis-coded scheme based on super orthogonal trellis codes (SOSTTC). It achieves full diversity and provides an improved coding gain. Moreover, there is no rate loss compared with trellis coded unitary space-time modulations. From the trellis structure of SOSTTC, we obtained a low-complexity and suboptimal differential decoder based on the per-survival processing technique (PSP). In slow fading channels, it can approach the performance of SOSTTC with coherent decoding. Furthermore, in time-varying channels, a bank of recursive least square (RLS) type channel predictors were incorporated into the Viterbi decoder to track the channel variance and the RLS predictors do not need the training data.

(iv). *Space-time trellis code design based on QAM-MTCM with trellis shaping*. We have extended super-orthogonal space-time trellis codes (SOSTTC), which are based on multiple trellis coded modulation (MTCM), to quadrature amplitude modulation (QAM) constellations. We obtained a systematic set-partitioning method for QAM constellations. Furthermore, trellis shaping based on set partitioning was incorporated in SOSTTC with QAM symbols to achieve extra shaping gain. This method can be extended directly to other space-time trellis codes based on QAM MTCM, such as

space-time trellis codes based on super quasi-orthogonal block codes with minimum decoding complexity (STTC-SQOBC-MDC). Peak constraints can be used to limit the constellation expansion ratio and peak-to-average power ratio (PAPR). When the data rate is high, simulation results show that about 0.5dB shaping gain can be achieved.

(v). *Space-time trellis code design based on super quasi-orthogonal block codes with minimum decoding complexity.* We proposed a new family of space-time trellis codes, which are constructed by combining a super set of quasi-orthogonal space-time block codes with minimum decoding complexity and an outer MTCM encoder. A systematic set partitioning method for QAM constellations was obtained. The proposed scheme can be used for systems with four and more than four transmit antennas. Furthermore, its decoding complexity is low because branch metric calculations can be done in a symbol-wise way. Simulation results demonstrate that the proposed scheme has a comparable performance as super quasi-orthogonal space-time trellis codes presented by Jafarkhani and Hassanpour while providing a lower decoding complexity.

B.5. Unitary Space-Time Block Codes

(i). *Best known 2 by 2 unitary space-time codes of size 16, 32, 64, 128, 256.* We obtained parametric unitary space-time codes and codes based on packing theory, in particular, we obtained the best known 2 by 2 unitary space-time codes for 2 transmit antennas of sizes 16, 32, 64, 128, 256. They codes have the best known diversity products in the literature.

(ii). *New Unitary Space-Time Code Designs from Sphere Packing Theory:* We have proposed some designs of 2 by 2 unitary space-time codes by using sphere packing theory. In particular, we have presented an optimal 2 by 2 unitary space-time code of size 6 in the sense that it reaches the maximal possible diversity product for 2 by 2 unitary space-time codes of size 6. The construction and the optimality of the code of size 6 provide the precise value of the maximal diversity product of a 2 by 2 unitary space-time code of size 6. Note that the optimal 2 by 2 unitary space-time codes of sizes above 5 and their diversity products were open in the literature.

B.6. Fast Decoding Algorithms

(i). *Fast iterative decoding algorithms for lattice based space-time coded MIMO systems and single antenna vector OFDM systems:* We obtained iterative demodulation and decoding methods for lattice based space-time coded systems concatenated with convolutional codes by first applying the optimal MAP demodulation and the suboptimal linear MMSE methods to lattice based space-time decoding and demodulation. We

then proposed two other methods based on the idea of soft interference cancellation and in one method scalar Gaussian approximation is used and in the other method vector Gaussian approximation is used. We also obtained the EXIT chart analyses for the performance analyses for these iterative methods. Both theoretical and simulation results show that the performance of the vector Gaussian approximation method is comparable to the linear MMSE method but in some cases the vector Gaussian approximation method has lower complexity. The complexity of the scalar Gaussian approximation method is the lowest among the different methods and grows linearly with the transmission rate while it still has an acceptable performance. Full diversity and full rate lattice based space-time coding is compared with the V-BLAST scheme and simulations show that the former one has a better performance than the later one even with the proposed suboptimal iterative demodulation and decoding methods.

(ii). *Iterative methods to exploit the signal space diversity.* Signal space diversity is a power and bandwidth efficient diversity technique. To exploit the signal space diversity, joint maximum-likelihood (ML) detection at the receiver is usually needed, where the complexity grows exponentially with the dimension of the lattice. In this work, we proposed a serial concatenated scheme and two simple iterative methods to exploit the signal space diversity. The simple iterative methods are based on the idea of soft interference cancellation. The first iterative method is based on a vector Gaussian approximation while the second one is based on a scalar Gaussian approximation. The complexity of the first iterative method grows cubically with the dimension of the lattice and the simulations show that its performance approaches that of the optimal MAP detection method. The complexity of the second iterative method grows linearly with the dimension of the lattice, and the simulations show that when the dimension of the lattice $N = 32$, at $\text{BER} = 10^{-5}$, the performance gap between the Rayleigh fading channel and the Gaussian channel is only 0.3 dB.

(iii). *Constellation mapping for space-time matrix modulation with iterative demodulation/decoding.* We investigated the mappings of bit-interleaved coded modulations with iterative demodulation/decoding (BICM-ID) when space-time constellations. Both coherent and non-coherent space-time modulations were considered. The *binary switching algorithm* was used to search optimized mapping when there is no *a priori* information and when there is perfect *a priori* information. Simulation results were shown to illustrate the effectiveness of the mapping optimization.

B.7. Others

(i). *Synchronization techniques and guard band configuration scheme for single-antenna vector OFDM systems*: Vector OFDM proposed by myself for single-antenna systems, is a generalization of conventional OFDM. It converts an ISI channel into multiple “ISI-free” vector channels and involves channel matrices instead of channel coefficients in one-tap equalization. Reduction in either cyclic prefix redundancy or the peak-to-average power ratio is achievable with proper vector OFDM configuration. This work addresses practical issues such as guard band configuration, timing estimation, and carrier and sampling frequency synchronization for vector OFDM. An equivalent structure derived for vector OFDM manifests the relation between vector OFDM and conventional OFDM so that the solutions to guard band configuration as well as carrier and sampling frequency synchronization for conventional OFDM can be modified to fit into the vector OFDM framework. It is also shown by analysis that the pre-FFT algorithms for timing estimation and carrier frequency synchronization in the conventional OFDM framework can be easily extended to vector OFDM with comparable performance. The performance advantage of vector OFDM is illustrated by simulation results of uncoded systems with ideal synchronization and with the same synchronization errors for both conventional OFDM and vector OFDM.

(ii). *Generalized Chinese remainder theorem from residue sets with errors with applications in sensor networks*. Chinese Remainder Theorem (CRT) has been recently generalized from determining a single integer from its remainders to determining multiple integers from their sets (residue sets) of remainders. We have considered the generalized CRT when the residue sets have errors. We first obtained a sufficient condition on the number of erroneous residue sets so that multiple integers can be still uniquely determined from their residue sets. We then proposed a determination algorithm of multiple integers from their residue sets with errors. Finally, we applied the newly proposed algorithm to multiple frequency determination from multiple sensors with low sampling rates and show the effectiveness of the proposed algorithm with considering residue set errors over the one without considering residue set errors.

C. Significance:

When single transmit antenna systems are well-understood, multiple transmit antenna systems have become an active research area in wireless communications. Similar to single transmit antenna systems, coding and modulation is one of the most important issues, if not the most important one, in such systems. Our contributions are mainly in the design of space-time codes for better performances. It is different from coding and

modulation in single transmit antenna cases, we have to deal with matrices instead of scalars, which raises the mathematical difficulty significantly. Our new designs of space-time codes provide better performance codes for multiple antenna wireless communications systems. Our results on unitary space-time codes, orthogonal space-time codes, and lattice based space-time codes will not only impact multiple antenna modulation designs in both military and commercial applications but also impact some areas in mathematics, such as sphere packing theory, compositions of quadratic forms and algebraic number theory.

D. Publications, Abstracts, Technical Reports, and Patent Disclosures or Applications

Refereed Journal Publications Supported by the Grant (Submitted)

44. Y. Li and X.-G. Xia, "A family of distributed space-time trellis codes with asynchronous cooperative diversity," submitted to *IEEE Trans. on Communications*.
43. H. Zhang, X.-G. Xia, Q. Zhang, and W. Zhu, "Iterative decision-aided clipping compensation and its application to scalable video transmission with multi-band OFDM," submitted to *IEEE Trans. Veh. Technology*.
42. Y. Li and X.-G. Xia, "On iterative decoding methods for lattice based space-time coded systems with EXIT chart analysis," submitted to *IEEE Trans. on Wireless Communications*.
41. H. Liao, H. Wang, and X.-G. Xia, "Some designs and normalized diversity product upper bounds for lattice based diagonal and full rate space-time block codes," submitted to *IEEE Trans. on Information Theory*.
40. D. Wang, H. Wang, and X.-G. Xia, "Space-time trellis code design based on super quasi-orthogonal block codes with minimum decoding complexity," submitted to *IEEE Trans. on Communications*.
39. S. Fu, H. Wang, and X.-G. Xia, "Recursive space-time trellis codes from general differential encoding," submitted to *IEEE Trans. on Information Theory*.
38. H. Wang, D. Wang, and X.-G. Xia, "On optimal quasi-orthogonal space-time codes with minimum decoding complexity," submitted to *IEEE Trans. Inform. Theory*.
37. H. Liao and X.-G. Xia, "Diversity product properties of Lu-Kumar's space-time codes," submitted to *IEEE Trans. Inform. Theory*.

36. S. Fu, X.-G. Xia, and H. Wang, "Recursive space-time trellis codes using differential encoding," submitted to *IEEE Trans. Inform. Theory*.
35. H. Zhang and X.-G. Xia, "Iterative decoding and demodulation with soft interference cancellation for single antenna vector OFDM systems," submitted to *IEEE Trans. on Veh. Technology*.
34. Y. Li, X.-G. Xia, R. Yao, and W. Zhu, "Iterative channel estimation for impulse radio ultra-wide band communication systems," submitted to *Wireless Personal Communications*.
33. H. Wang and X.-G. Xia, "A New Formula of Singular Value Decompositions with Application in Hermitian Compositions," submitted to *Linear Algebra and Its Applications*.
32. H. Wang, W. Su, and X.-G. Xia, "Orthogonal-like space-time coded CPM systems for three and four antennas with fast decoding," submitted to *IEEE Trans. on Information Theory*.

Refereed Journal Publications Supported by the Grant (Published and Accepted)

31. K. Lu, S. Fu, and X.-G. Xia, "Closed form designs of complex orthogonal space-time block codes of rates $(k+1)/(2k)$ for $2k-1$ or $2k$ transmit antennas," *IEEE Trans. on Information Theory*, (the associate editor has emailed us to accept it.).
30. X.-G. Xia and K. Liu, "A generalized Chinese remainder theorem for residue sets with errors and its application in frequency determination from multiple sensors with low sampling rates," *IEEE Signal Processing Letters*, to appear.
29. W. Zhang, X.-G. Xia, and P.-C. Ching, "Clustered pilot tones for carrier frequency offset estimation in OFDM," *IEEE Trans. Wireless Communications*, to appear.
28. D. Wang and X.-G. Xia, "Super orthogonal differential space-time trellis coding and decoding," *IEEE Journal on Selected Areas in Communications*, to appear.
27. H. Zhang, X.-G. Xia, L. Cimini, and P. C. Ching, "Synchronization Techniques and Guard Band Configuration Scheme for Single-Antenna Vector OFDM Systems," *IEEE Trans. on Wireless Communications*, to appear.
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13. A. Song and X.-G. Xia, "Decision Feedback Differential Detection for Differential Orthogonal Space-Time Modulation with APSK Signals over Flat Fading Channels," *IEEE Trans. on Wireless Communications*, Nov. 2004.
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11. W. Su, X.-G. Xia, and K. J. R. Liu, "A Systematic Design of High-Rate Complex Orthogonal Space-Time Block Codes," *IEEE Communications Letters*, June, 2004.
10. G. Wang and X.-G. Xia, "An Orthogonal Space-Time Coded CPM System with Fast Decoding for Two Transmit Antennas," *IEEE Trans. on Information Theory*, March 2004.
9. H. Wang and X.-G. Xia, "Upper bounds of rates of complex orthogonal space-time block codes," *IEEE Trans. on Information Theory*, Oct. 2003.
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5. G. Fan and X.-G. Xia, "Wavelet-Based Texture Analysis and Synthesis Using Hidden Markov Models," *IEEE Trans. on Circuits and Systems I*, vol. 50, pp. 106-120, Jan. 2003.
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H. Appendix: Some Selected Publications

REPORT DOCUMENTATION PAGE

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1. REPORT DATE (DD-MM-YYYY) 1-8-2005		2. REPORT TYPE Final		PERIOD COVERED (From - To) 1-3-2002 - 31-3-2005	
4. TITLE AND SUBTITLE Space-Time Code Designs for Broadband Wireless Communications				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER F49620-02-1-0157	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Xiang-Gen Xia				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Electrical and Computer Engineering University of Delaware Newark, DE 19716				8. PERFORMING ORGANIZATION REPORT NUMBER UODECE SF298REPORT 1-8-05	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research (AFOSR)				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES N/A					
14. ABSTRACT This report describes the main research achievements during the time period cited above on the research project in the area of telecommunications. The main achievements include new rate upper bounds of orthogonal space-time block codes (OSTBC), systematic and closed-form designs of high rate OSTBC, orthogonal space-time coded continuous phase modulations, optimal full diversity and/or minimum maximum-likelihood decoding complexity quasi OSTBC, optimal cyclotomic space-time block code designs, some optimal unitary space-time block codes, new space-time trellis codes, new families of recursive space-time trellis codes using differential encoding, some fast decoding methods of lattice-based space-time coding, and a family of full diversity distributed space-time trellis codes for asynchronous cooperative communication systems etc.					
15. SUBJECT TERMS space-time coding, complex orthogonal designs, cyclotomic space-time codes, fast iterative decoding, quasi-orthogonal space-time codes, asynchronous cooperative communications					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 11	19a. NAME OF RESPONSIBLE PERSON Xiang-Gen Xia
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) 302-831-8038